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Highway Noise Criteria Study: Technical Summary

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Physics Division
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[Spo]nsored by:
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

This report summarizes, at the request of the Federal Highway Administration, a multifaceted research program carried out by the acoustics staff of the National Bureau of Standards. The program was designed to (1) identify and quantify the important physical parameters associated with time-varying highway noise caused by various densities of both free-flowing and stop-and-go traffic conditions; (2) investigate, evaluate and compare measures and computational procedures for rating time-varying noise in terms that are relevant to human response; and (3) determine by means of a laboratory study which among several time-varying rating schemes best predicts the acceptability and annoyance caused by traffic noise as heard both outdoors and indoors. The results of this program are briefly described and the implications of the major findings discussed.

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1. INTRODUCTION

This technical summary was prepared at the request of the Federal Highway Administration. It briefly outlines and describes a multifaceted research program carried out by the Acoustics Staff of the National Bureau of Standards. One of the major goals of this research program was to ascertain which among several time-varying noise descriptors best quantifies highway noise and predicts the annoyance caused by exposure to it. Details concerning each phase of the program have been fully documented in the published reports listed at the end of this technical summary. Accordingly, the following pages only briefly summarize the content of each of the already published documents.

As will be seen below, the most important findings of this research program can be summarized in the following manner: (1) the simpler time-varying noise descriptors such as the equivalent sound level (L_{eq}) and the level exceeded 10 percent of the time (L_{10}) are, in the case of traffic noise, as good as, if not better than, more complicated schemes incorporating either the range of variability or rate of change of levels with time; (2) for highway noise the choice of which frequency weighting is utilized is not critical since one frequency weighting may be predicted from another with very little uncertainty; (3) so long as the equivalent sound level (L_{eq}) is at or below 50 dB under laboratory conditions, over half of the exposed people find the traffic sound always acceptable; (4) when the equivalent sound level is 55 dB or greater, over half of the exposed people find the traffic noise unacceptable.

In view of the above findings it appears that in the case of time-varying highway noise the measurement and computational complexity associated with schemes incorporating the range of variability or rate of change in levels with time are unwarranted.

1.1 Background

Social surveys have consistently shown that of all the highway impacts, noise from highways and urban traffic disturbs the public most. Recognition of the annoyance to the public caused by traffic noise has led Congress to direct the Secretary of Transporation, through an amendment to Title 23 of the United States Code, Section 109(i), to promulgate highway noise standards. The Federal Highway Administration (FHWA) promulgated noise standards for highways in 1973, (revised in 1976, 1978 and 1982) in Procedures for Abatement of Highway Traffic Noise and Construction Noise, 23 CFR 772.

During the development of its highway noise standards the FHWA considered the environmental, social, and economic impacts of various noise levels. Hearing impairment and the general adverse response to noise exposure were considered to be the most relevant aspects of human response to highway noise. Based upon the data base available then it was concluded that community exposures to traffic noise were not severe enough to induce hearing impairment. However, the same data base indicated that the most important impact of traffic noise was on the general adverse response, defined as a combination of several factors such as speech interference, sleep interference, the desire for quiet, and the ability to use satisfactorily the telephone, radio and television.

While insufficient information existed then regarding the effects of time-varying noise on people, a large body of data was available on the effects of steady-state noise exposure on speech communication. Since many of the factors involved in the general response to noise exposure are related to activity interference, especially speech communication, the effect of steady-state noise on speech communication became the basis for selecting highway noise criteria.

When FHWA promulgated its highway noise criteria it recognized that speech interference caused by steady-state noise was an insufficient basis for standards applying to predominantly time-varying noise. Hence, FHWA committed itself to a future reevaluation of these noise standards as research data on the effects of time-varying highway noise became available. Accordingly, FHWA requested participation by the National Bureau of Standards (NBS) in a study designed to provide important data bases required by FHWA for this reexamination. The results of this joint FHWA/NBS research are summarized herein.

1.2 Goals of the Study

This research program was designed to (1) identify and quantify the important physical parameters associated with time-varying noise caused by various densities of both free-flowing and stop-and-go traffic; (2) investigate, evaluate, and compare measures and computational procedures for rating time-varying noise either in use or proposed; (3) determine by means of a laboratory psychoacoustic study which among several time-varying noise ratings best predicts human response to actual samples of traffic sounds; and, (4) if none of the noise-rating indices adequately predict human response, develop an improved procedure based upon the data obtained in the psychoacoustic study.

1.3 Organization of the Study

In view of the rather large scope of the study the work was organized in a series of discrete phases. First, in order to identify and quantify the important physical parameters associated with time-varying highway noise, analog recordings of actual traffic sounds were made at several times of day, at several sites selected to represent a variety of highways.

Second, since traffic noise is often a cause of disturbance in the home, it was felt that, in order to obtain useful data on the effects of time-varying highway noise on people, it would be desirable to present traffic sounds to subjects as heard both outdoors and indoors. Hence, the second phase of the study involved a series of sound pressure measurements obtained simultaneously indoors and outdoors at several locations at each of several dwellings. From these data an electronic filter was developed which simulated the average sound isolation of residential building shells in the Washington, D.C. area.

Third, in order to identify which aspects of time-varying noise may affect human response and how these parameters can be incorporated into a noise-rating scheme, an in-depth review of the literature dealing with the effects of time-varying noise on people was undertaken.

Fourth, a psychoacoustic study was conducted to assess the response, as measured in the laboratory, of adult subjects to three-minute samples of traffic sounds and to evaluate the accuracy of selected noise-rating procedures in predicting these responses.

The major thrust of the FHWA/NBS Study centered upon the temporal aspects of highway noise. However, in view of the large body of data acquired during the course of the study and the general tendency to use the A-weighted level to account for the differential sensitivity of people to various frequency bands, the relationships among major frequency-weighting schemes and the A-weighted level were explored through analysis of the data bases acquired during the first phase of the program.

2. SUMMARY OF THE HIGHWAY NOISE STUDY

The procedures utilized and the data obtained during the course of this program are fully documented in Refs. 1-5. Only a brief description of each phase of the work is given below.

2.1 Traffic Noise Data Base (Ref. 1)

Fifteen minutes of analog recordings of actual traffic sounds were made at four microphone positions at each of seven sites selected to represent a variety of highways. The criteria used to select the sites, the site characteristics, and the methods used to obtain and analyze the library of actual traffic sounds are given in Secs. 2 and 4 of Ref. 1. Complete descriptions of the sites are given in Appendix A while the data bases are documented fully in Appendix B and C of Ref. 1.

Five of the chosen sites had nominally constant-speed traffic while the other two corresponded to stop-and-go intersection traffic. During each recording session all microphones were located 1.2 m above the ground at distances of 7.5, 15, 30, and 60 m from either the nearest lane of traffic along a line perpendicular to the highway (for constant speed traffic) or at the same distances along a line bisecting the angle formed by the two highways (for stop-and-go intersection traffic).

A total of 107 traffic recordings was obtained, each lasting 15 minutes. These were subsequently analyzed in the laboratory so as to yield graphic plots and digital records of sound pressure levels as a function of time. These data were themselves extensively analyzed.

During each recording session, video recordings of traffic flow were also made to count and classify vehicles (i.e., number of automobiles, medium trucks, and heavy trucks in each traffic direction).

To obtain graphic plots of the A-weighted sound level, the electrical signal from the tape recorder was fed into a precision sound level meter set for "fast" A-weighted response. The detected root-mean-square output from the sound level meter was fed into a graphic level recorder set for DC response and having a writing speed sufficiently fast to enable the pen to follow closely the signal from the sound level meter. Figure 1 illustrates the data that were obtained in this manner.

To obtain digital records of sound pressure levels, the signal from the tape recorder was fed also into a real-time 1/3-octave band analyzer where the signal was analyzed as A-weighted levels and as 1/3-octave band sound pressure levels for the frequency range having center frequencies from 25 Hz to 16 kHz. For these analyses the integration time was set to 0.1 s. Outputs from the analyzer were sent to a minicomputer for format and storage on digital tape.

The digital tapes were processed on the NBS central computer facility after being edited for questionable runs and/or extraneous noise events (e.g., horns blowing, shouting, airplanes). The digitized sound levels were exponentially smoothed to obtain data corresponding closely to the levels that would have been obtained with a precision sound level meter set for "fast" response. Using these exponentially-smoothed, digitized 1/3-octave band sound pressure levels, cumulative probability distribution plots of A-weighted sound pressure levels observed during each recording were obtained. An example of the distribution plot is shown in Fig. 2.

In addition, the A-weighted sound pressure levels for each 30-s time block and for the entire 15-minute duration of each recording were tabulated, as were the levels exceeded 1, 10, 50, 90, and 99 percent of the time, the traffic noise index (TNI), the standard deviation of levels around the mean value (σ), the equivalent sound level (L_{eq}), the noise pollution level (NPL), the rate of change of levels with time (dL/dt) and two equivalent sound levels incorporating a correction for the rate of change of levels with time: L_{eq}' and L_B. An example of these data is shown in Table 1. A definition of each of these noise descriptors is given in the appendix to this technical summary.

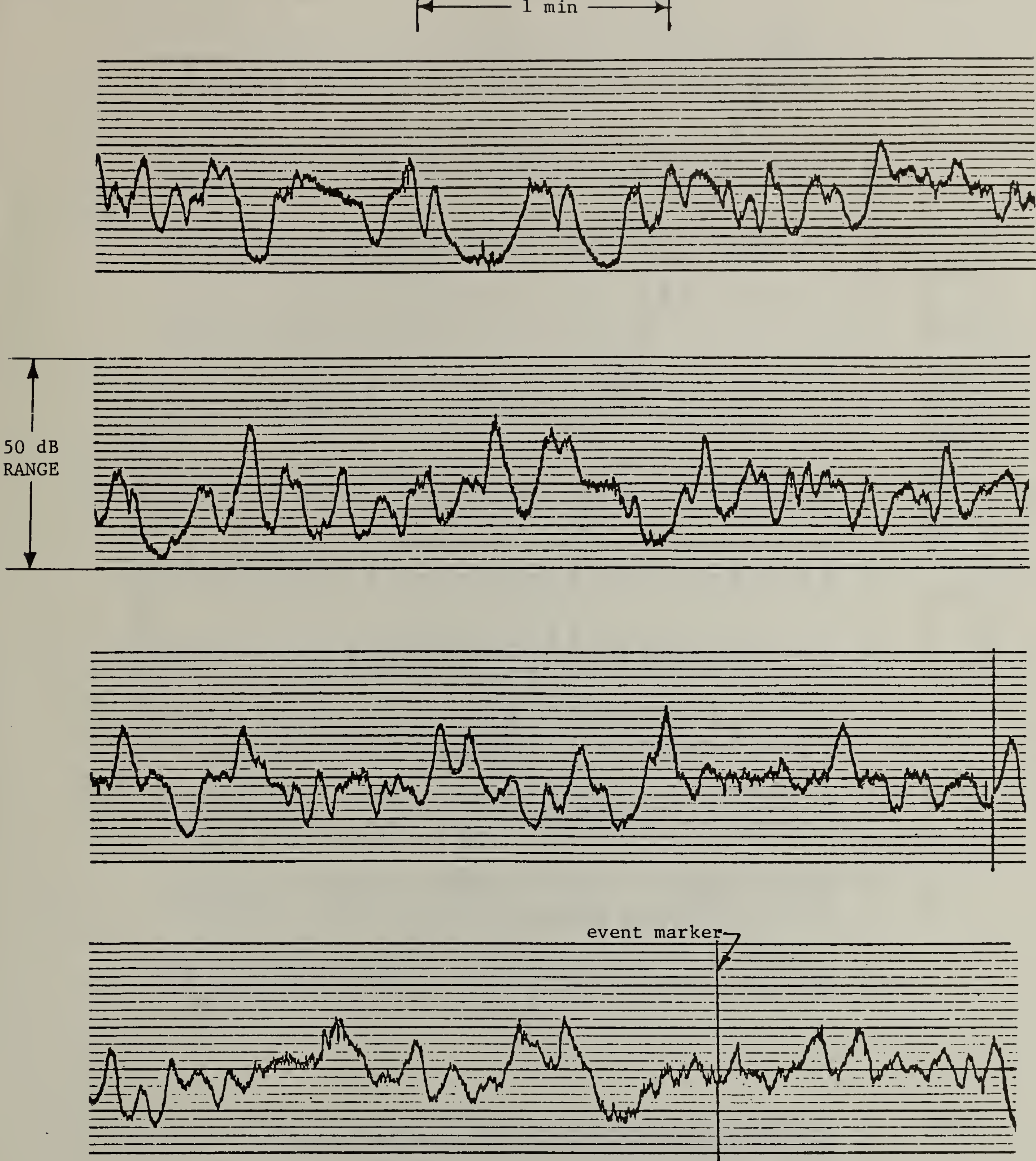

Figure 1. A-weighted sound pressure level time history for the GUDE DR. site, 16 June 1977, 1600 hrs., 15-m microphone.

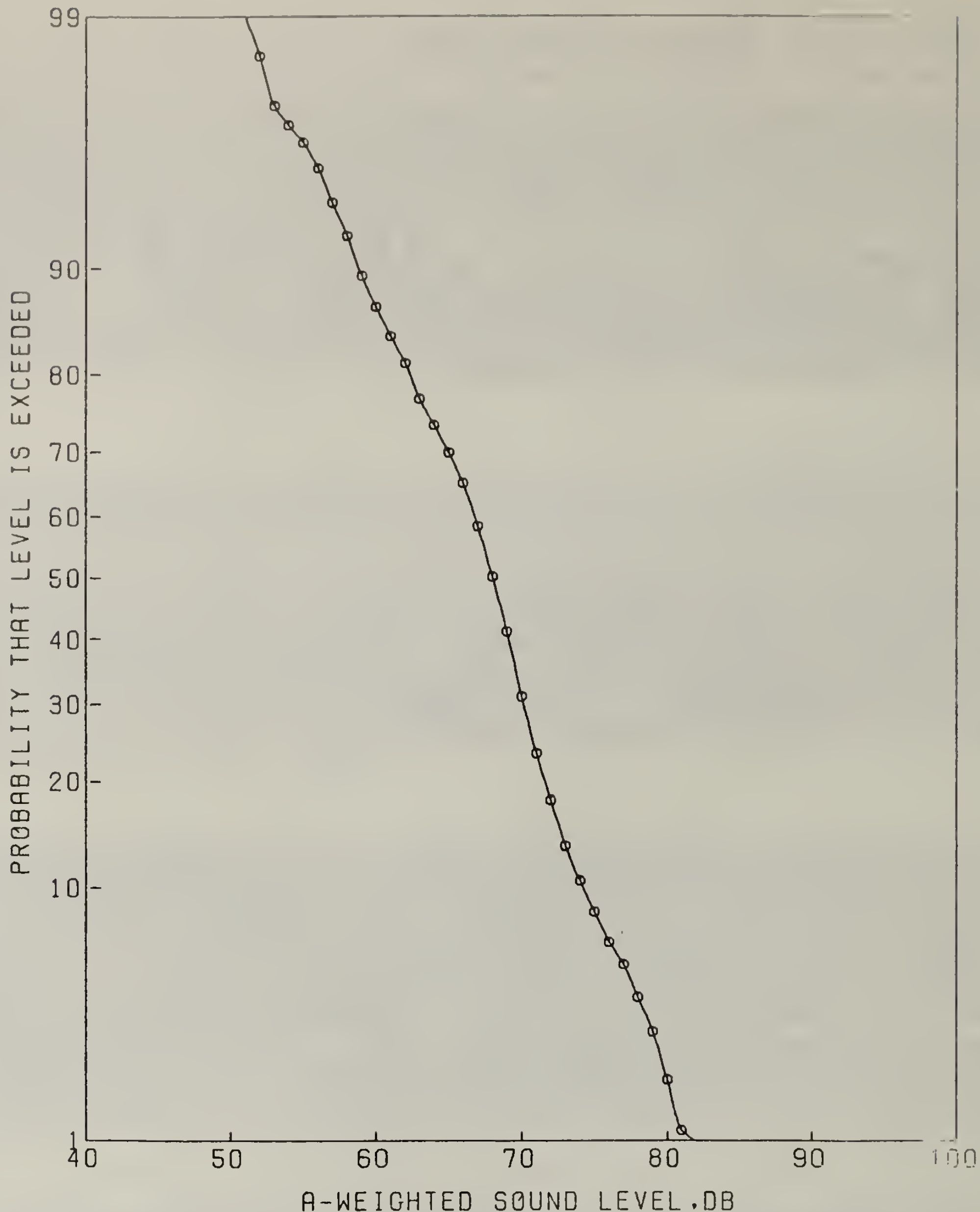

Figure 2. Cumulative probability distribution of A-weighted sound pressure levels for the GUDE DR. site, 16 June 1977, 1600 hrs., 15-m microphone.

TIME BLOCK	NOISE DESCRIPTOR(FROM AWT) L1	L10	L50	L90	L99	TNI	LEQ	SIG	TDR	LNP	LEQP	LB
1	69.0	67.2	63.1	60.5	59.6	57.6	64.2	2.5	1.4	70.6	77.6	91.6
2	67.2	65.4	61.9	59.0	58.2	54.6	62.7	2.4	1.6	68.8	76.6	91.0
3	71.0	66.2	64.1	62.0	60.5	48.8	64.7	1.9	2.6	69.4	80.6	97.7
4	68.9	64.8	62.5	61.0	60.5	46.2	63.1	1.6	1.5	67.2	76.9	91.6
5	69.5	67.4	63.9	62.0	60.9	53.5	64.9	2.2	1.4	70.5	78.5	92.4
6	77.5	71.4	66.0	64.0	63.1	63.8	68.4	3.2	3.0	76.5	85.1	104.0
7	73.2	69.7	66.0	63.7	62.2	57.7	67.2	2.5	2.4	73.7	82.9	99.4
8	68.2	66.3	64.0	62.6	61.6	47.4	64.4	1.4	1.3	68.1	77.7	91.6
9	87.3	80.2	64.5	62.2	61.5	104.1	75.4	7.4	3.8	94.4	93.0	116.0
10	80.8	76.5	64.4	61.5	60.6	91.6	71.3	6.3	4.0	87.4	89.1	111.1
11	67.1	65.7	62.1	60.1	59.5	52.3	63.0	2.1	1.3	68.4	76.1	90.0
12	67.1	65.9	64.0	62.0	61.2	47.8	64.2	1.4	1.0	67.8	76.3	87.7
13	67.2	65.0	62.4	60.6	59.6	48.4	62.9	1.8	1.1	67.5	75.5	88.5
14	69.9	66.5	63.3	59.6	58.5	57.1	63.9	2.8	1.2	70.9	76.5	90.1
15	70.5	67.5	63.0	60.2	58.8	59.4	64.6	3.0	2.2	72.2	79.9	96.0
16	66.4	65.3	63.7	62.4	61.6	44.1	63.9	1.1	1.1	66.7	76.3	88.2
17	74.1	69.4	66.8	63.7	62.6	56.5	67.6	2.5	2.1	74.0	82.8	99.6
18	76.0	70.6	65.9	63.9	62.5	60.9	68.0	3.0	2.2	75.6	83.3	100.8
19	74.5	70.1	65.0	61.9	60.6	64.9	66.9	3.1	1.6	74.8	80.9	97.1
20	74.2	70.7	65.6	62.7	61.6	64.5	67.6	3.2	1.6	75.8	81.6	97.4
21	76.0	71.4	67.7	64.5	63.0	62.2	68.7	2.8	2.4	75.9	84.4	102.1
22	69.2	65.9	63.3	61.9	60.9	47.8	64.0	1.7	1.7	68.3	78.3	93.9
23	73.5	70.2	66.0	63.5	60.7	60.3	67.3	2.8	1.5	74.4	81.0	96.3
24	72.1	69.2	66.3	64.8	63.8	52.5	67.1	1.8	1.9	71.7	81.9	97.2
25	71.3	68.1	64.5	63.1	62.5	52.9	65.6	2.1	1.7	70.9	79.8	94.9
26	71.5	69.5	64.8	62.5	61.6	60.4	66.3	2.7	1.3	73.2	79.4	92.6
27	71.4	68.6	65.6	63.7	62.6	53.1	66.2	1.9	2.2	71.0	81.4	98.2
28	71.0	67.8	63.1	61.6	60.6	56.5	64.9	2.7	1.5	71.7	78.6	93.6
29	64.4	63.2	61.9	60.7	59.8	40.6	62.0	.9	1.0	64.3	73.9	85.6
TOTAL	76.4	68.9	64.4	61.4	59.4	61.3	67.2	3.3	2.0	75.6	82.1	103.6

Table 1. Noise descriptors at 30-second intervals - 355 and Q.O. RD. site, 24 June 1977, 1600 hrs, 15-m microphone.

Using the digitized 1/3-octave band sound pressure levels over the frequency range from 50 Hz to 10 kHz, time-averaged spectra were computed for the levels exceeded 1, 10, 50, 90, and 99 percent of the time and for the equivalent band sound pressure levels (L_{eq}) for the entire duration of each sample. These data were tabulated and graphed as illustrated in Table 2 and Fig. 3.

Included among the sites selected for inclusion into the study were 3 interstate highways, 2 secondary roads, and 2 intersections. Accordingly, the data obtained were grouped for further analyses into 3 categories, corresponding to these types of highway. Table 3 summarizes the traffic conditions prevailing at the three types of highways during the recording periods.

During the review of the literature dealing with human response to time-varying noise (see Sec. 2.4 below) it was found that the equivalent sound level (L_{eq}), the level exceeded 10 percent of the time (L_{10}), the noise pollution level (NPL), the traffic noise index (TNI), and two equivalent sound levels adjusted for the rate of change of levels with time (L_{eq}' and L_B) were deserving of further investigation. Accordingly, for each of these time-varying noise descriptors, the minimum, mean, and maximum values observed for each type of highway were computed as a function of distance of the microphone from the center lane of traffic. The data obtained are summarized in Table 4. Examples are presented graphically in Figs. 4-6, together with the range of variations observed at each microphone location.

The major finding of this phase of the FHWA/NBS research program can be seen by inspection of Table 4, which reveals that, independent of the type of highway or microphone position, L_{eq} and L_{10} behave in a similar manner, with L_{10} being typically 2 to 4 dB larger than L_{eq}. In general, L_{eq}', L_B, and NPL show a slightly more rapid falloff with distance than do L_{eq}, or L_{10}. Further, TNI was found to fall off with distance much more rapidly than any of the other descriptors and yielded a much larger range of values than all other descriptors included in these analyses.

2.2 Outdoor/Indoor Noise Isolation (Ref. 2)

In order to determine how outdoor traffic sounds are modified when heard by listeners located indoors, outdoor-to-indoor noise isolation measurements were conducted at 9 single-family dwellings located in the greater Washington, D.C., area. The test house parameters are summarized in Table 5.

Since these measurements were performed to provide the data base required for developing a house filter for use in the presentation of psychoacoustic stimuli, emphasis was placed upon obtaining data at probable listener locations. Hence, the measurements performed differed significantly from either standardized or proposed procedures where, typically, the emphasis is on determining the sound insulation of either a building facade or of building elements.

FREQUENCY	1/3 OCTAVE BAND LEVEL					
	LEQ	L1	L10	L50	L90	L99
50	71.0	79.5	74.5	68.4	63.7	60.6
63	71.5	79.1	74.5	69.5	64.8	61.8
80	73.2	81.5	76.5	70.8	66.0	62.3
100	72.6	80.5	75.7	70.6	65.9	62.7
125	70.8	79.7	73.1	67.7	63.3	60.1
160	69.5	78.6	71.8	66.7	62.2	59.2
200	66.6	76.1	69.2	64.1	60.0	57.1
250	63.8	73.5	66.5	60.9	57.0	54.1
315	61.0	70.7	63.6	57.5	53.4	50.7
400	57.6	67.2	60.4	54.9	50.9	48.5
500	54.9	63.6	57.4	52.8	49.6	47.3
630	54.1	62.0	56.4	52.6	49.7	47.5
800	54.9	63.0	56.7	53.4	51.0	49.0
1000	58.4	67.3	56.5	53.0	50.8	48.8
1250	57.1	65.4	56.5	52.9	50.6	48.4
1600	55.5	64.5	56.2	52.3	49.9	48.0
2000	54.5	63.8	54.8	50.7	48.3	46.6
2500	52.8	62.9	53.6	49.3	46.7	44.8
3150	51.1	60.9	52.3	47.5	44.9	43.5
4000	49.8	59.0	50.9	45.7	42.9	.0
5000	46.9	55.7	48.7	44.0	.0	.0
6300	45.3	54.0	47.1	42.8	.0	.0
8000	44.0	51.6	45.1	.0	.0	.0
10000	43.7	49.5	42.9	.0	.0	.0

Table 2. 1/3-octave band spectra for the 355 and Q.O. RD. site, 24 June 1977, 1600 hrs., 15-m microphone, recording duration of 14.2 min.

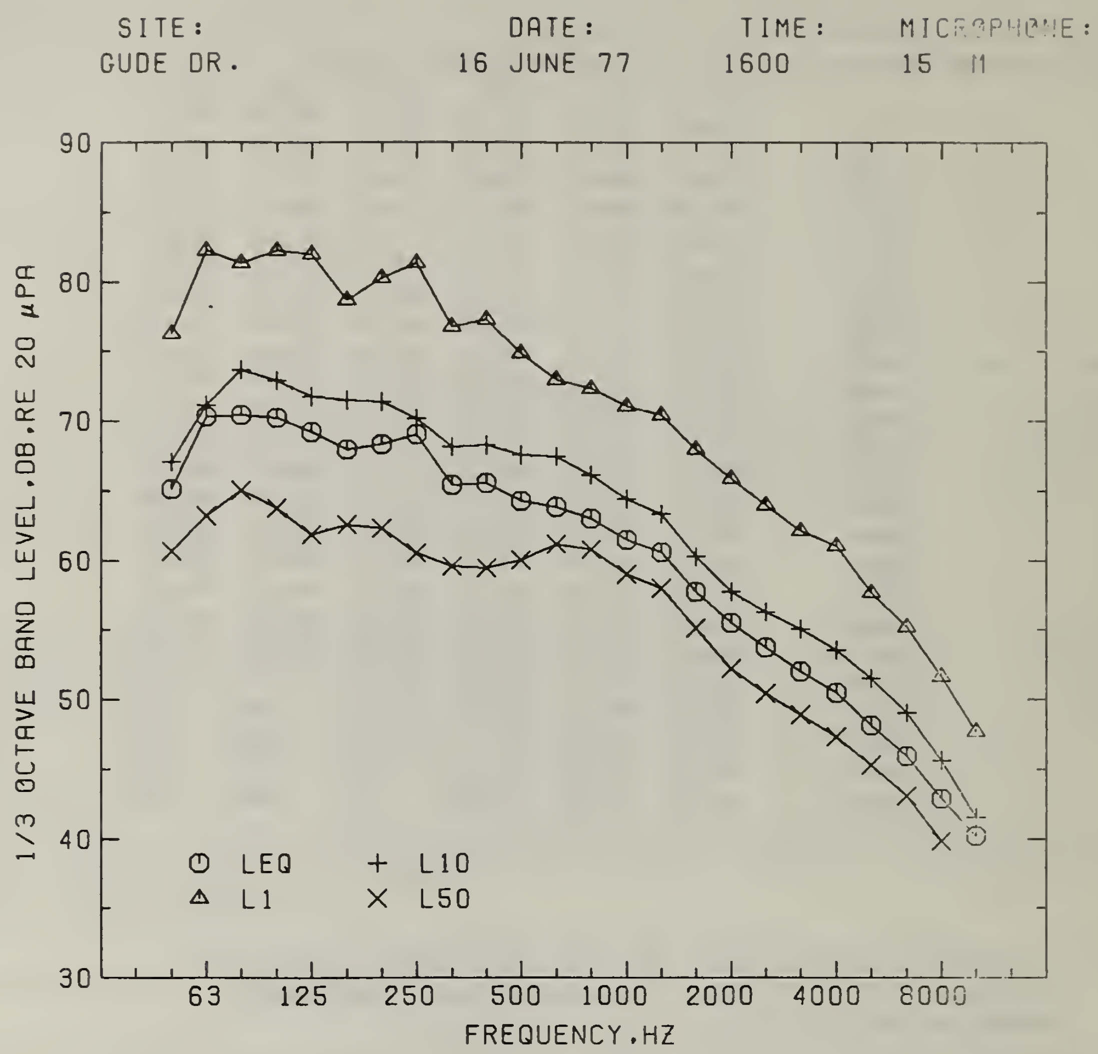

Figure 3. 1/3-octave band L_{eq}, L_1, L_{10}, and L_{50} spectra for the GUDE DR. site, 16 June 1977, 1600 hrs., 15-m microphone, recording duration of 14.5 min.

Table 3. Summary of traffic conditions for actual-traffic noise recordings

Type of Highway	Interstate			Secondary			Intersection		
Sites (No. Lanes)	COMSAT(4) I95(8) B-W PKWY(4)			RT. 28(2) GUDE DR.(2)			355 & SHADY GR.(-) 355 & Q. O. RD.(-)		
Traffic Parameter	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Average Traffic Speed,km/hr	85	90	93	61	67	71	-	-	-
Total Traffic Volume,veh./hr	1990	3020	4330	660	1010	1430	2760	3680	5380
Percent Automobiles	77.4	91.9	98.6	84.2	90.8	94.6	88.3	93.2	98.1
Percent Medium Trucks	1.0	2.8	7.1	3.2	4.9	6.4	1.7	4.3	6.5
Percent Heavy Trucks	0.0	5.3	15.5	1.6	4.3	9.8	0.2	2.5	5.2

Table 4. Summary of six of the descriptors of the A-weighted sound levels for the actual-traffic noise recordings.

Type of Highway		Interstate			Secondary			Intersection		
Sites		COMSAT I95 B-W PKWY			RT. 28 GUDE DR.			355 & SHADY GR. 355 & Q. O. RD.		
Descriptor	Mike	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
LEQ	7.5m	72.1	77.5	82.0	69.3	73.0	76.1	70.1	71.6	73.7
	15m	65.3	71.1	78.5	62.0	67.1	70.7	65.5	68.6	71.8
	30m	58.3	66.5	72.2	55.3	59.7	62.9	61.4	64.4	67.4
	60m	62.4*	66.1*	69.1*	51.7	54.1	56.9	58.3	60.5	63.1
L10	7.5m	75.9	80.6	85.2	71.1	75.6	79.2	73.0	74.4	76.2
	15m	68.5	74.7	82.4	65.1	69.5	77.2	67.4	71.0	73.9
	30m	60.8	69.4	76.0	57.7	62.1	66.5	63.3	66.4	69.6
	60m	65.7*	69.4*	72.6*	51.3	55.8	59.3	59.9	62.4	65.5
LEQP	7.5m	91.3	96.3	101.2	87.6	91.5	93.9	86.6	88.1	89.7
	15m	83.1	88.8	94.0	79.3	84.4	87.7	79.3	84.0	87.8
	30m	72.8	81.3	88.2	70.7	74.9	78.1	74.4	79.0	82.9
	60m	77.0*	80.6*	83.4*	66.8	68.8	71.9	70.5	74.4	77.7
LB	7.5m	112.4	116.8	122.9	107.9	111.3	112.5	105.1	107.3	109.7
	15m	100.3	107.6	115.3	97.7	102.7	105.9	95.5	102.8	107.1
	30m	89.6	97.4	105.8	88.6	92.5	95.2	90.1	97.2	102.2
	60m	92.7*	95.6*	98.4*	82.2	85.8	89.9	84.1	90.8	95.8
LNP	7.5m	89.2	93.6	102.6	88.6	93.5	100.9	79.7	82.5	84.1
	15m	77.2	84.9	96.8	79.2	84.9	90.1	72.1	78.4	82.3
	30m	67.9	76.9	87.9	68.0	72.8	77.6	66.9	72.9	77.3
	60m	73.1*	76.6*	80.3*	61.1	65.0	71.4	62.8	67.7	72.2
TNI	7.5m	81.4	97.5	120.7	93.6	106.1	127.8	70.7	75.2	78.0
	15m	68.9	83.7	110.6	78.0	91.7	106.1	54.8	67.7	74.7
	30m	52.2	69.8	94.1	67.7	69.9	83.7	47.5	59.0	65.6
	60m	61.3*	70.7*	77.8*	47.4	54.8	59.3	41.4	51.2	59.5

* The data for Interstate highways do not include recordings at the 60-m microphone position for the B-W PKWY site.

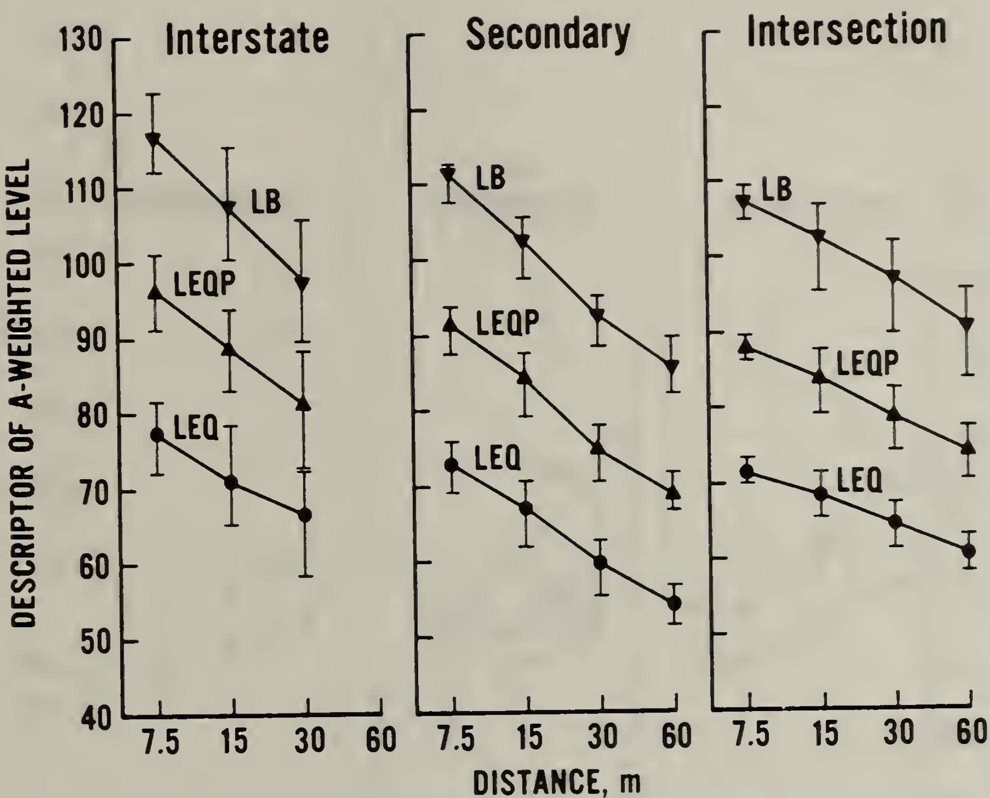

Figure 4. Variation of observed values of L_{eq}, L_{eq}', and L_B with distance for interstate and secondary highways and for intersections. The solid symbols represent the average ratings over all recordings at all sites of a given type. The error bars represent the ranges of the ratings.

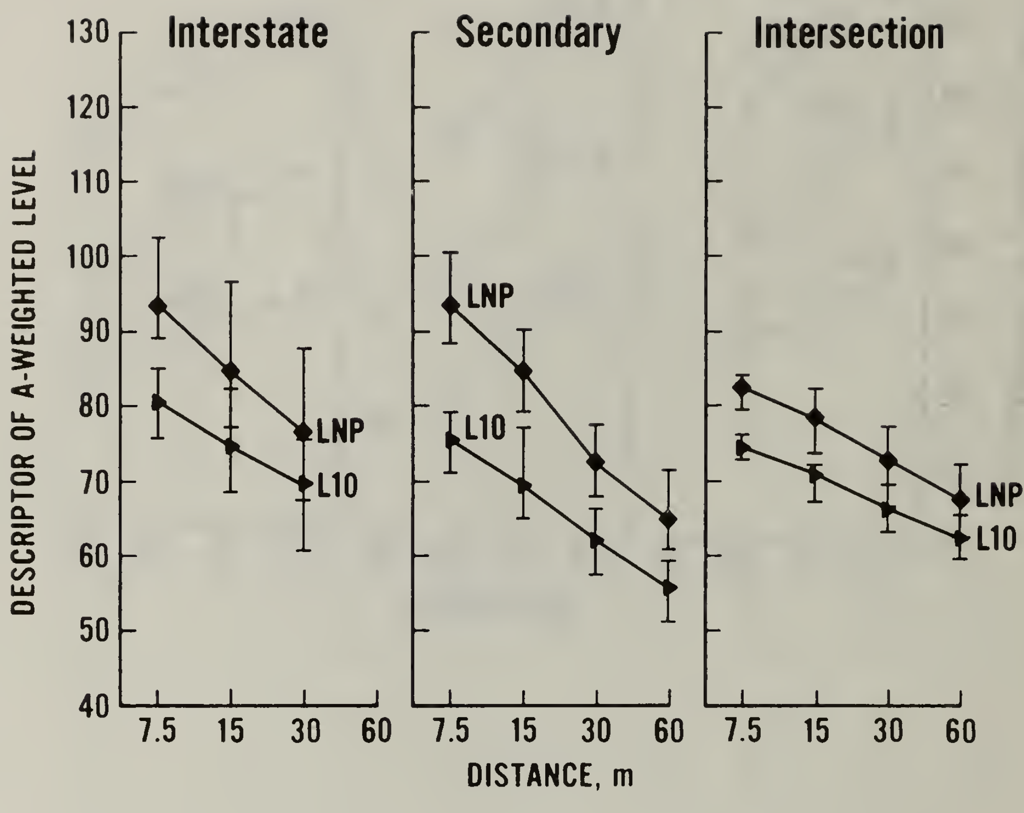

Figure 5. Variation of observed values of L_{10} and NPL with distance for interstate and secondary highways and for intersections.

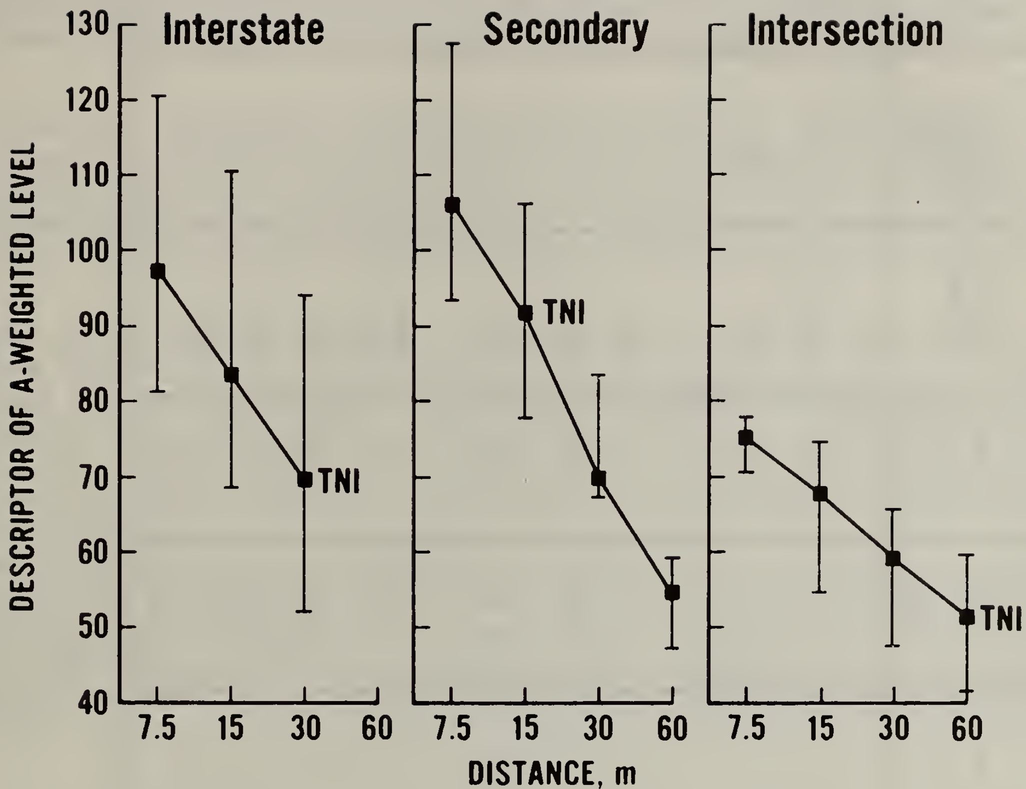

Figure 6. Variation of observed values of TNI with distance for interstate and secondary highways and for intersections.

Table 5. Summary of test house parameters.

House No.	Construction	Outside Door	Window Area Front (m^2)	Window Area Side (m^2)	Total (m^2)	Storm Window	Room Volume (m^3)	Distance To Street (m)
1	Brick Veneer (Partial Height[a])	Front	3.4	0	3.4	Partial	55	11
2	Brick Veneer (Full)	None	3.6	0	3.6	None	64	20
3	Brick Veneer (Partial Height[a])	Front	3.3	0	3.3	Full	64	61
4	Stone Veneer (On Front Only)	None	3.4	0	3.4	None	54	20
5	Frame	Front	2.7	1.1	3.8	Full	43	13
6	Brick Veneer (On Front Only)	Side (2 doors)	2.3	2.7	5.0	None	72	14
7	Brick Veneer (Partial Height[a])	Front	3.5	1.1	4.6	Full	51	15
8	Frame	Side	3.9	2.6	6.5	None	83	24
9	Frame	Front	4.5	1.1	5.5	Full	48	15

a/ To Top of Window

The major difference between the procedure utilized in this study and those normally used is that in the present study interior microphone positions were deliberately chosen so as to yield the spatial averaged mean-square pressure over probable listener positions rather than at locations chosen to yield the average over the entire volume of the test room. Accordingly, a sound isolation metric dubbed "Noise Intrusion Reduction" (NIR) was defined to avoid confusion with current definitions of sound isolation and sound insulation.

By definition, the Noise Intrusion Reduction, NIR, is the difference between the outdoor time-varying sound pressure level and the sound pressure level at a listener position or averaged over a number of listener positions in the receiving room. Hence, the NIR does not include terms to adjust for either the size of the partition or the receiving room absorption.

Details covering the measurement procedures used in this study can be found in Secs. 2 and 3 of Ref. 2. Suffice it to say here that, at each of the selected houses, simultaneous analog tape recordings were obtained of the sound pressure at seven microphone positions, three located outdoors and four indoors, while a small NBS truck was driven past the test house at a nominal speed of 48 km/hr (30 mph). Since the truck produced insufficient signal indoors at high frequencies, the truck spectrum was supplemented with "pink noise" broadcast through loudspeakers. The loudspeakers were placed on the van step on the opposite side of the vehicle from the driver. In this position the loudspeakers were approximately 0.75 m above the pavement. With the addition of the supplemental pink noise, sufficient interior noise was obtained to determine the noise isolation provided by the building shells over the frequency range from 50 Hz to 4 kHz.

The exterior and interior analog sound pressure recordings for each of the nine test houses were reduced to 1/3-octave band sound pressure levels according to three processing methods. The first method was designed to produce 1/3-octave band sound pressure level time histories for the individual vehicle passbys. The second method yielded the maximum sound pressure level occuring in each 1/3-octave band during an individual vehicle passby. The third method was designed to yield the average 1/3-octave band levels obtained by averaging the squared sound pressure over an 8-second interval during each passby. This was done so as to allow for the computation of the sound exposure level (SEL) during each passby at each microphone position.

The three sets of data obtained in the manner discussed above were used to derive for each building facade the NIR values in each 1/3-octave band over the range extending from 31.5 Hz to 4 kHz. The resulting data are given in Appendices B, C and D of Ref. 2. A graphical illustration of the type of data obtained using each of the processing methods is illustrated here in Fig. 7.

The data presented in Appendices B, C and D of Ref. 2 were subjected to intense scrutiny in order to determine which among the three sets should be utilized to derive the desired house filter. The results of these analyses are discussed in Sec. 4 of Ref. 2. Suffice it to say here that the NIR values obtained using the maximum sound pressure level in each 1/3-octave band during each passby yielded the best data from the point of view of run-to-run consistency and maximum signal-to-noise ratio. For these reasons further analyses were carried out using the data obtained by this method.

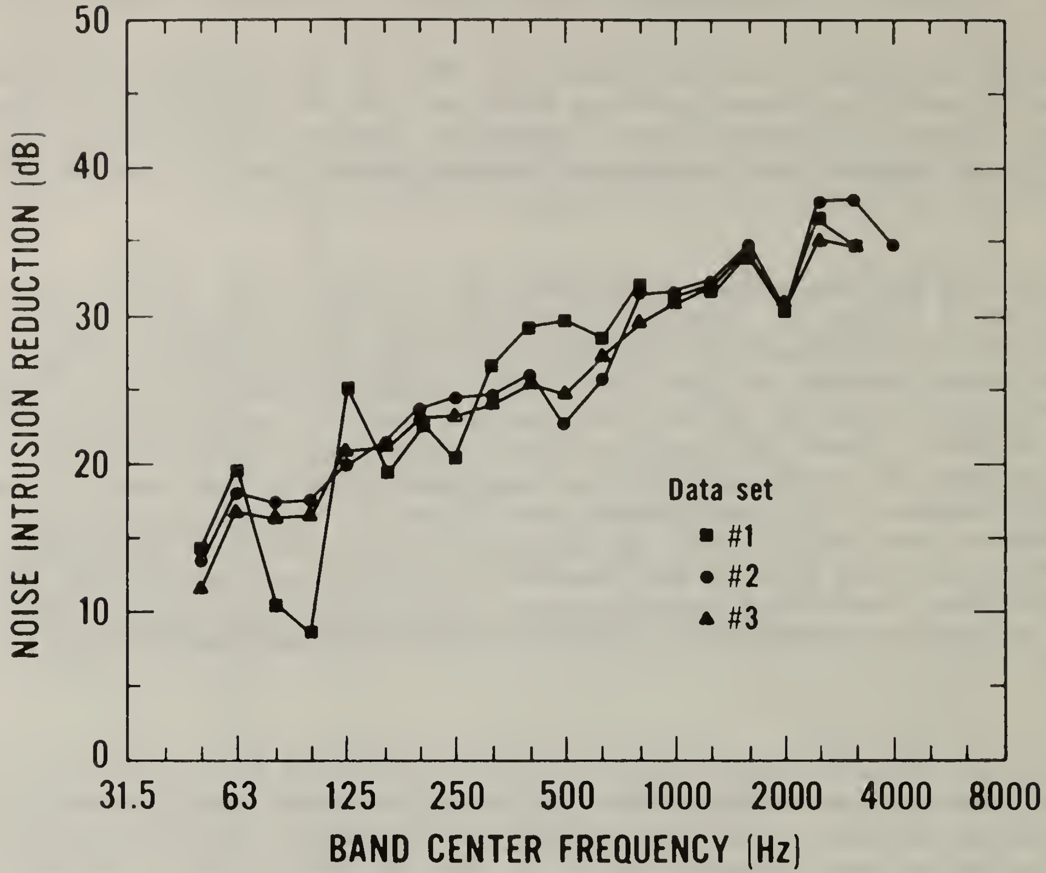

Figure 7. Noise Intrusion Reductions, for the three different data sets, at Test House No. 6.

Data Set No. 1. Computed from simultaneous 1/3-octave band levels at the time of maximum interior A-weighted level.

Data Set No. 2. Computed from the maximum 1/3-octave band levels, regardless of when they occurred.

Data Set No. 3. Computed from 1/3-octave band sound exposure levels.

The average NIR values in each 1/3-octave band for the set of all nine houses were computed. Those data are presented in Fig. 8, together with the range of NIR values in each 1/3-octave band for average values for individual houses and the range for individual microphone positions for all nine houses. Inspection of Fig. 8 shows that the range in the average NIR values for individual houses is less than 10 dB in all 1/3-octave bands except those centered at 40, 100, and 125 Hz.

The NIR values obtained in this study were compared to noise isolation data published in the literature. These comparisons revealed that the data obtained compared favorably to published data for constructions located in cold climates. Neither the data obtained here nor those published for cold climates compared favorably to noise isolation data published for construction in warm climates. Hence, the electronic house filter derived in the present study, according to procedures described in Appendix E of Ref. 2, is more representative of the Noise Intrusion Reduction provided by dwellings in colder climates than in warmer climates. The frequency response of this filter is shown in Fig. 9. Inspection of Figs. 8 and 9 shows that the frequency response of the electronic filter over the frequency range extending from 50 Hz to 4 kHz simulated the average NIR values for the nine test houses included in the study, and had a nominally flat frequency response above and below these frequencies.

2.3 Effects of Time-Varying Noise on Annoyance

One of the major goals of the FHWA/NBS study was to examine, evaluate, and compare measures and computational procedures for rating time-varying noise in terms that are relevant to human response. Accordingly, while the physical measurement program was underway, an in-depth review of the literature dealing with human response to time-varying noise was undertaken, noise rating procedures were identified, and a psychoacoustic study was designed. The following sections outline the major findings of this literature review and the results of the psychoacoustic study.

2.3.1 Literature Review (Ref. 3)

Over the last 30 years or so, numerous studies of the effects of environmental noise on people have been conducted in this country and abroad. These studies are reviewed in detail in Ref. 3; only major findings are summarized here.

Two main approaches have been utilized to achieve a better understanding of human response to time-varying environmental noise. The first approach has involved field investigations in which, typically, the environmental noise levels are measured, on a continuous or intermittent basis, throughout a community and a social survey is conducted to assess the effects of the noise on the impacted population. The second approach has been to investigate under laboratory conditions the effects of a particular environmental noise parameter (e.g. number and/or duration of discernable noise events, intermittency) on a specific human response such as speech interference and annoyance.

Most social surveys have resulted from public expression of dissatisfaction with either the introduction of a new noise source or system in the environment or as a result of a significant increase in the noise producted by an existing system. Hence, most social surveys were designed to assess the annoyance and/or

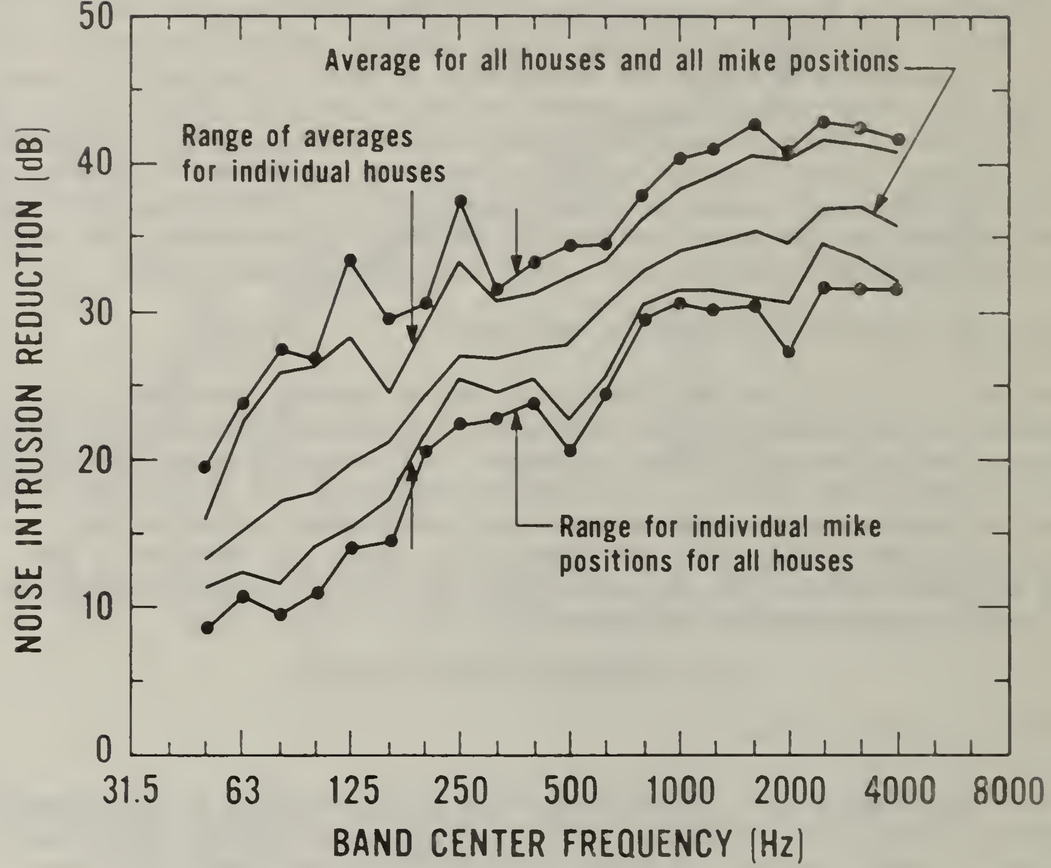

Figure 8. Average and range of Noise Intrusion Reduction values for all nine test houses.

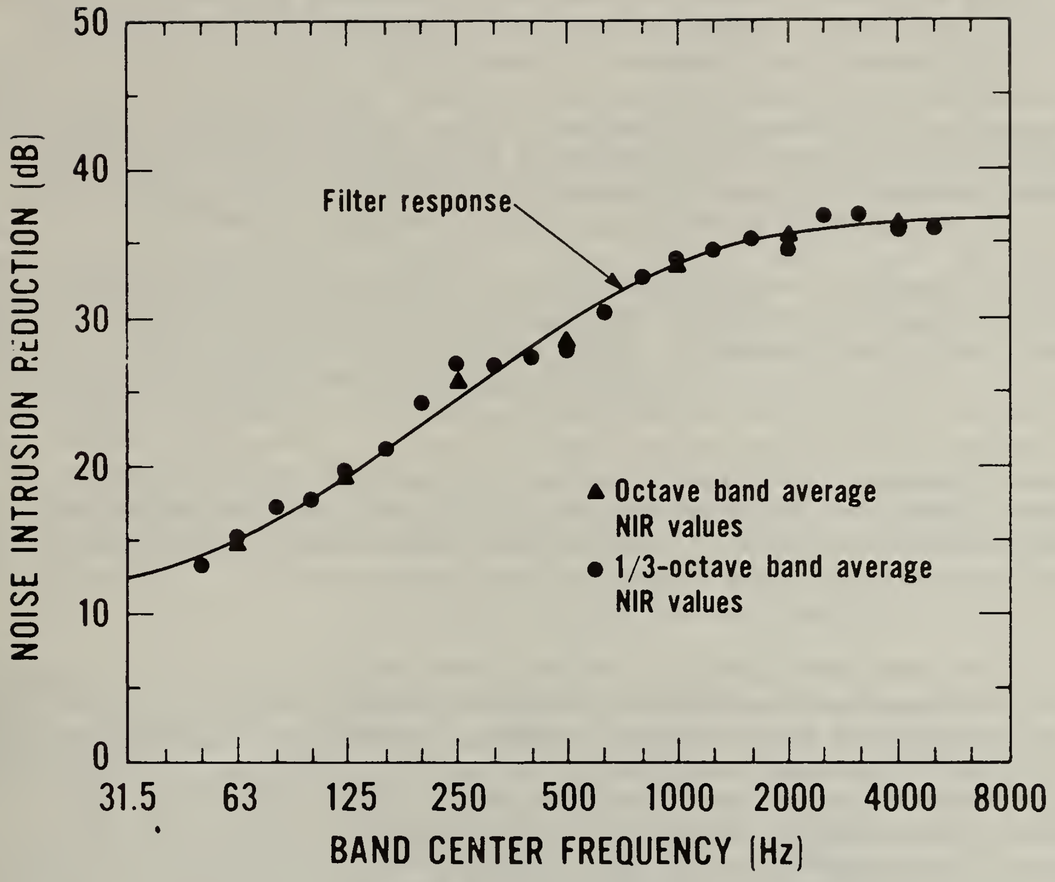

Figure 9. Outdoor-to-indoor noise reduction simulated by an electronic "house filter."

community response produced by a specific noise source. The result has been the development of diverse methods for expressing the relationship between human response and the physical attributes of the noise. During the last decade researchers have become more aware of the need to develop a unified noise-rating index that would apply to all environmental noises independently of the noise source.

A common result of social surveys is that people exposed to noise in their homes show a generalized adverse response which increases with increasing noise exposures. This generalized response is complex and involves a combination of factors including speech interference, sleep interference, a frustrated desire for quiet, and inability to use telephone, radio, and telèvision. Thus, one major factor contributing to annoyance frequently involves activity interference. Other factors involved include socio-economic parameters (e.g., sex, age, education, income bracket) as well as other ill-defined parameters.

In view of the complexity of human response to time-varying environmental noise, it is not suprising that while the <u>average</u> response of homogeneous groups of people can be predicted reasonably well, individual responses cannot. Social survey data consistantly show that in the aggregate the <u>average</u> response of groups of people is highly correlated with a number of noise-rating indices, with correlation coefficients often greater than 0.9. These high correlations arise in part because all noise-rating indices increase with increasing sound pressure levels. On the other hand, individual response scores are consistently unpredictable with correlation coefficients between individual scores and noise exposure levels typically being about 0.4.

Several attempts have been made to explore the relationship between individual personality traits and noise induced annoyance; however, the results of these studies are unclear and many questions remain unanswered. For example, while social survey data show that approximately 10 to 15 percent of the population is always bothered by noise, no matter how quiet it is, a similar percentage of people are never annoyed no matter how loud the environment is. No explanation of this phenomenon has been forthcoming. Some researchers have argued that the relationship between annoyance and noise exposure is modified by intervening variables such as fear and misfeasance while others using the same data base have not been able to show such intervention.

Another major social survey finding is that in many instances people are able to identify, when interviewed, the specific noise that annoys them most. However, the same data also show that the annoyance produced by a specific noise source, such as an airport, is influenced by the presence of another noise source, such as a freeway. The relationship between the two noise sources or systems and annoyance is complex and dependent upon several factors such as the relative levels of the two sources, and the intermittency of one relative to the other. Moreover, the relationship between annoyance and a particular noise source is influenced by the time of day during which the exposure occurs. For example, there is a general consensus among researchers that noise events occurring at night are more annoying than the same events occurring during the daytime. However, recent findings suggest that people are more annoyed with events occurring in the evening rather than at night. Exposures to noise during evening hours have not been studied systematically and most noise-rating indices do not account for evening hours.

Although considerable data have been gathered through field investigations, all that can be said with any degree of confidence is that there exists a relationship between community noise exposure and annoyance. However, this relationship depends partly on the character of the noise and partly on other-ill defined parameters that may or may not bear a relationship to the noise. Much remains to be learned about the etiology of noise-induced adverse response. This is perhaps the reason why, during the late 1960's and the 1970's, more and more researchers have turned toward the laboratory for answers.

Laboratory studies have been used to investigate the effects of human response of such parameters as the number of noise events discernible in a background noise, the variability in the noise levels during the period of observation, the rate of interruption in the noise exposure, the interaction of various noise sources as, for example, the superimposition of aircraft noise on traffic noise. Again the primary purpose of these studies was to gain sufficient insight into the etiology of noise-induced annoyance in order to develop noise-rating indices for predicting human response to noise from measurable physical parameters of the noise. The major findings of these studies are described in detail in Ref. 3 and are only summarized below.

The adverse response to time-varying noise exposure, as measured in the laboratory, is not only dependent upon the sound pressure level but also upon other physical parameters of the noise, especially the number of discrete noise events and intermittency. Unfortunately, the relationship between measured annoyance and either interruption rate or number of events is complex and nonmonotonic.

It appears that below a certain "threshold", in either the rate of interruption or the number of discernible noise events, the adverse response to noise is unaffected by these parameters. However, when the rate of interruption and/or number of events reaches a certain level, annoyance appears to increase with the rate of interruption and/or the number of events until an upper threshold is reached. Above this threshold further increases in either interruption rate and/or number of events do not influence annoyance or, sometimes, even result in a decrease in annoyance. Within the range where increases in the interruption rate or the number of discernible events contribute to increased annoyance, the relationships between these factors and annoyance vary from study to study and among types of noise sources.

Although some researchers argue strongly that variability in the noise levels during the observation period contributes to annoyance, the data examined showed that in many instances variability per se had little effect on measured annoyance. In some instances the more variable noises were found to be less annoying than steady-state noises presented at the same average level. Further, when the offending noises originate from two different and distinct systems, level-dependent interactions between the resulting noises occur and this in turn affects the measured annoyance in a complex manner that varies from study to study.

While laboratory studies have been very useful in identifying those parameters of time-varying noise that potentially affect annoyance, the relative contributions of these parameters to annoyance are unclear; accordingly, the development of rating schemes that adequately account for these parameters has not been forthcoming. Nevertheless, during the last 10 years, the proliferation of environmental noise indices has been recognized as a major impediment to the

development of meaningful noise control and abatement programs since, in the absence of a unified metric to measure all noise exposures, environmental noise goals are difficult to express. Thus, the shift in recent years has been toward reanalyses of existing data bases with the aim of arriving at a general environmental noise descriptor. These efforts were also reviewed in Ref. 3.

Despite the fact that numerous noise indices have been put forth for characterizing environmental noise, no consensus has been reached as to which best predicts human response to noise. Moreover, careful examination of these various indices reveals that for all practical purposes the large number of indices can be grouped into three general categories. The first category is predicated upon the assumption that exposure to the same equivalent sound levels, L_{eq}, over a fixed period of time will produce equivalent adverse human response.

The second category of noise indices is predicated upon the assumption that while the general response to time-varying noise increases with increasing sound levels, it also is affected by the extent of the variability in the sound levels during the period of observation. For some of the indices that fall in this category (e.g., NPL) the equivalent sound level (L_{eq}) is adjusted by adding a measure of the extent of variability in sound levels. Other indices are expressed in terms of some statistical description of the observed sound levels (e.g., L_{10} and TNI).

The third category is based upon the assumption that while the adverse response to time-varying noise increases with the equivalent sound level, people's sensitivity to how rapidly the levels change during the observation period is important and must be incorporated into the noise-rating. Indices falling in this category, typically, adjust the equivalent sound level (L_{eq}) by adding a term that is a function of the rate of change of levels with time (dL/dt).

Each of the general noise rating categories discussed above emphasizes different aspects of time-varying noise. Thus, predictions of human response given by each category of descriptors vary. Further, as one moves from the first category to the last, both the physical measurement and computational procedures required significantly increase in complexity. In view of the lack of firm evidence for adopting one scheme over another it was decided that the psychoacoustic study should be designed to assess how the various schemes predict human response under controlled conditions.

2.3.2 Laboratory Study (Ref. 4)

Upon completion of the literature survey, six noise-rating procedures were selected from among the three general categories of noise descriptors and a psychoacoustic study was designed to assess which among these descriptors best predicts human response to time-varying noise. Included among the noise-rating procedures tested were the equivalent sound level (L_{eq}), the level exceeded 10 percent of the time (L_{10}), the traffic noise index (TNI), the noise pollution level (NPL), and two indices incorporating a measure of the rate of change of level with time (L_B and L_{eq}'). Details concerning this study are given in Ref. 4; only a brief review is given below.

Twenty-eight audiologically normal adult subjects were required to judge both the annoyance caused by and the acceptability of 3-minute exposures to 12 samples of recorded sounds, presented as recorded (but with selected frequency-independent attenuations) and as modified by the house filter described above. The experiment was conducted in the NBS realistic listening room. Annoyance judgments were obtained through the use of a magnitude estimation technique. Specifically, subjects were required to indicate how annoying traffic sounds were by assigning a number from 1 to 10 after hearing each stimulus, with smaller numbers being assigned to the less annoying sounds. Acceptability judgments were obtained by having the subjects check on a scoring sheet a box entitled either "acceptable" or "unacceptable".

In the course of the experiment each subject was required to judge 24 acoustic stimuli 4 times, yielding a total of 96 annoyance and 96 acceptability judgments per subject. From the data thus obtained, annoyance scores for each of the stimuli were computed. A one-way analysis of variance was performed and disclosed that the 3-minute segments of traffic noise were perceived by the subjects as being significantly different from one another. This analysis also indicated that 73 percent of the variance observed in the annoyance scores was attributable to the stimuli themselves.

Moreover, since the main purpose of the experiment was to assess how each selected environmental noise-rating index predicted the measured annoyance, the A-weighted L_{eq}, L_{10}, L_{eq}', L_B, NPL, and TNI for each of the 24 three-minute stimuli were computed from physical analyses of these traffic sounds as played-back into the listening room. The results of these computations are shown in Table 6.

Regression analyses were performed to assess how well each noise related with the measured annoyance. Linear regression parameters for each noise rating are documented in Ref. 4 and are summarized here in Table 7. Inspection of Table 7 shows that the product-moment correlations (r) were high in all cases, rating from 0.99 to 0.93, with TNI showing a slightly smaller value (r = 0.83).

Further analyses using techniques developed for interdependent correlation coefficients were carried out. These revealed that while all the noise-rating procedures predicted annoyance scores well, the accuracy of the predictions varied. Specifically, L_{eq}, L_{10}, and L_{eq}' accounted for 96 to 98 percent of the variance in the annoyance ratings while NPL and L_B accounted for 86 to 90 percent, and TNI did worst with only 69 percent of the variance in the annoyance scores accounted for. The relationships among the various noise-ratings were also very high, as summarized in Table 8 which shows the correlation coefficients among the various noise indices.

The second set of judgments, that is the acceptability judgments, were analyzed independently from the annoyance judgments using similar techniques. The data obtained revealed that so long as the equivalent sound level, L_{eq}, was at or below 50 dB over half of the subjects found the stimuli "always acceptable"; however, stimuli having L_{eq} values greater than about 55 dB were judged as

Table 6. Computed A-weighted noise rating values for the three-minute time-varying highway noise stimuli as presented to the subjects in the listening room.

Stimulus	L_{eq}	L_{10}	L_{eq}'	NPL	L_B	TNI
1	65.6	69.0	80.8	77.0	95.7	73.7
2	43.6	46.2	56.4	50.1	70.1	36.7
3	70.0	73.0	84.5	79.4	98.7	72.9
4	45.9	48.2	58.9	52.3	72.1	38.3
5	71.7	74.8	90.3	85.8	108.8	86.9
6	51.5	55.5	70.6	63.9	89.1	60.3
7	58.4	61.5	76.4	74.8	96.3	79.7
8	45.6	47.8	62.5	55.4	82.5	44.8
9	63.3	65.1	79.9	73.7	99.7	63.8
10	52.0	53.8	68.4	61.7	88.0	50.0
11	63.9	64.4	80.5	74.0	102.5	60.1
12	48.3	48.7	64.6	56.7	85.9	38.4
13	61.1	62.7	76.3	68.2	94.7	51.9
14	45.8	46.8	59.5	50.7	75.5	32.3
15	58.7	61.6	76.5	77.6	96.1	89.6
16	46.4	48.3	63.0	57.4	82.8	48.0
17	56.1	58.6	71.7	66.8	91.9	60.4
18	46.5	48.7	61.8	55.3	81.8	43.4
19	56.0	59.2	72.2	68.8	89.5	68.4
20	44.4	46.6	59.5	52.2	77.0	38.8
21	56.8	59.2	71.1	65.0	85.5	54.5
22	40.4	41.3	51.7	43.4	63.0	19.3
23	68.6	72.9	86.0	85.2	104.5	94.7
24	55.7	60.2	72.9	71.2	91.8	78.4

Table 7. Results of linear regression analyses between annoyance rating scores and noise indices.

	L_{eq}	L_{10}	L_{eq}'	NPL	L_B	TNI
product moment correlation (r)	0.99	0.98	0.98	0.95	0.93	0.83
amount of variance accounted for (r^2)	0.98	0.98	0.96	0.90	0.86	0.69

Table 8. Matrix of correlations between noise indices.

	L_{eq}	L_{10}	L_{eq}'	NPL	L_B	TNI
L_{eq}	---	0.99	0.99	0.96	0.93	0.84
L_{10}		---	0.99	0.97	0.93	0.88
L_{eq}'			---	0.98	0.97	0.87
NPL				---	0.96	0.95
L_B					---	0.87
TNI						---

"always unacceptable" by over half the subjects. Accordingly, a demarcation line between two categories of either acceptable or unacceptable traffic sounds, as heard indoors in the laboratory, occurred somewhere between L_{eq} = 50 and L_{eq} = 55 dB.

The most significant finding of the psychoacoustic study was that, for the type of noise studied here, the simpler noise measurement and rating schemes such as L_{eq} and L_{10} correlate very well with annoyance as measured in the laboratory. This suggests that within the constraints of this experiment the most important factor contributing to both annoyance and acceptability is by far the sound pressure level. Further, since both L_{eq} and L_{10} are highly correlated with annoyance, and since all other rating schemes studied are highly correlated with each other and with L_{eq} and L_{10}, it appears that the measurement and computational difficulties associated with the more complex schemes are unwarranted.

2.4 Relationships Among Frequency Weightings (Ref. 5)

A series of calculations was performed to ascertain how well one frequency-weighted rating, such as a weighted sound level, a loudness level, or the perceived noise level, may be predicted from another such rating. A total of 103 average sound level spectra selected from the recordings discussed above in Section 2.1 were used in these computations. It was found that knowing a single frequency rating, such as the A-weighted sound level, enables one to predict other outdoor frequency ratings with a standard deviation of the order of 1 to 2 dB. If, in addition, traffic speed, mix and the distance to the highway are taken into account, these standard deviations can be reduced to 0.5 to 1 dB, depending upon the particular frequency noise rating of interest. Equations are given in Ref. 5 for predicting one rating from another; the associated standard deviations are presented as a measure of how well any given rating can be predicted from a single measured, or otherwise known, noise rating. It is concluded that the choice of a frequency-weighting procedure is not critical in conjunction with highway noise since one descriptor can be predicted from another with a small statistical uncertainty. Thus, if human response criteria, or stimulus-response relationships, have been developed in terms of one frequency-weighting procedure, these criteria may be translated into equivalent criteria expressed in terms of a frequency metric that is easier to measure or predict.

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APPENDIX. DEFINITIONS OF TIME-VARYING NOISE DESCRIPTORS

This appendix contains mathematical definitions of time-varying noise descriptors discussed in the main body of this technical summary. In all instances the term $L(t)$ denotes the A-weighted sound level as a function of time.

1. L_n (e.g. L_1, L_{10}, L_{50}, L_{90}, L_{99}) is the A-weighted sound level re 20 μPa in decibels, exceeded n percent of the time, where $n = 1, 10, 50 \ldots\ldots$

2. Traffic Noise Index (TNI)

$$TNI = L_{90} + 4(L_{10} - L_{90}) - 30. \tag{1}$$

3. Equivalent Sound Level (L_{eq})

$$L_{eq} = 10 \log_{10}\left[\frac{1}{T}\int_0^T 10^{L(t)/10}dt\right], \tag{2}$$

where T is the total time of observation and $L(t)$ is the A-weighted sound level at time t.

4. Noise Pollution Level (NPL)

$$NPL = L_{eq} + k\sigma \quad , \tag{3}$$

where L_{eq} is as in Eq. (2), σ is the standard deviation of the population of A-weighted sound levels observed during the period of observation, and k is an empirical constant selected to be 2.56.

5. L_{eq}'

$$L_{eq}' = L_{eq} + f(\sigma'), \tag{4}$$

where L_{eq} is as in Eq. (2) and $f(\sigma')$ is a function of the root-mean-square value of dL/dt, the rate of change of sound level with time. That is,

$$\sigma' = \left[\frac{1}{T}\int_0^T (dL/dt)^2 dt\right]^{1/2}, \tag{5}$$

where T is the observation time, and

$$f(\sigma') = A \log_{10} (1 + B\sigma') \quad , \tag{6}$$

where A = 10 and B = 15 s

6. L_B

$$L_B = k \log_{10}\left[\frac{1}{T}\int_0^T p_B{}^2(t)dt\right], \tag{7}$$

where k is a constant, T is the time of observation, and

$$p_B(t) = \int_{-\infty}^{+\infty} g(t-\tau)p(\tau)dt \ , \tag{8}$$

in which $(t) = 10^{L(t)/2k}$ and g is the Fourier transform of a weighting function $G(\omega)$.

For $G(\omega) = 1$, $L_B = L_{eq}$.

For $G(\omega) = 1 + i\omega\beta$,

$$L_B = k \log_{10}\left\{\frac{1}{T}\int_0^T \left[1 + \tau^{*2} \ (dL/dt)^2\right] 10^{L(t)/k} dt\right\}, \qquad \text{(Eq. 10)}$$

where $\tau^* = (\beta/2k \ln 10)$ is a time constant which determines the limit beyond which rates of change of the sound level, dL/dt, contribute significantly to the noise index value. For this study τ^* was set equal to 15 s.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report summarizes a multifaceted research program carried out by the acoustics staff of the National Bureau of Standards at the request of the Federal Highway Administration. The program was designed to (1) identify and quantify the important physical parameters associated with time-varying highway noise caused by various densities of both free-flowing and stop-and-go traffic conditions; (2) investigate evaluate and compare measures and computational procedures for rating time-varying noise in terms that are relevant to human response; and (3) determine by means of a laboratory study which among several time-varying rating schemes best predicts acceptability and annoyance caused by traffic noise as heard both outdoors and indoors. The results of this program are briefly described and the implications of the major findings discussed.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Acoustics; general adverse response to noise; noise measurement; Sound.

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